Analysis of Alternative Service Measures for Freeway Facilities

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ABSTRACT

The Year 2000 U.S. *Highway Capacity Manual* (HCM2000) will incorporate new procedures for the analysis of directional freeway facilities. The data base for developing this chapter provides the opportunity to analyze directional freeway facilities with undersaturated and oversaturated flow conditions, over both temporal and spatial dimensions. That chapter will also incorporate the revised HCM2000 analytical procedures for basic freeway, ramp, and weaving sections. Determining facility-based measures of effectiveness (MOE) is often a difficult proposition. A major concern in aggregating MOE for freeway facilities over time and space is how and when to combine them under both undersaturated and oversaturated conditions. Varying flow conditions may occur across segments and/or time intervals. This affects the reporting of traditional service measures of effectiveness with respect to aggregation and sensitivity. This paper reviews the technical literature on facility-based MOE, and explores alternative service measure aggregation techniques using field data, in order to overcome some of the pitfalls associated with MOE aggregation.

1. INTRODUCTION AND BACKGROUND

Directional freeway facilities consists of several contiguous freeway segments that are classified as basic, ramp or weaving segments. Until the recent development effort associated with the HCM2000, previous capacity manuals did not have contain a procedure to analyze such facilities. Rather, the HCM methods were limited to individual segments and to single time periods. They did not account for the interaction between segments over time (e.g., peak hour build-up), or space (queue spillback from downstream segments). In 1997, the U.S. Federal Highway Administration sponsored a research study to develop procedures for capacity and LOS analysis for directional freeway facilities. This research resulted in the development of a new HCM2000 chapter on freeway facilities and in a research-quality software package, FREEVAL, that faithfully implements the procedure in computer code (May 1998). The freeway facility MOE estimation procedure is grounded in macroscopic theories of traffic flow including input-output and shock wave analyses. Capacity is explicitly derived from the corresponding chapters on basic, ramp, or weaving segments.

This paper is organized as follows. A brief literature review on the development of facility-wide MOE is given. Next, the field data sets used in the directional freeway facility study are described, followed by the application of various aggregation techniques and their effects on the facilities' MOE. A cumulative distribution approach is then described, and applied to the data sets. The results are discussed and implications are drawn for future work.

2. LITERATURE REVIEW

There is a large body of knowledge regarding the analysis of overall system performance of freeway facilities. Studies conducted to date have focused on two entities: performance measures and service measures. The Draft HCM 2000 describes performance measures as "quantitative measurements of system outcomes" which may serve as a measure of traveler satisfaction, or quality of service, such as travel time or delay (1998a). Service measures, or measures of effectiveness (MOE), are those performance measures "used by the Highway Capacity Manual to assign a letter grade (A–F) to the quality of service," such as density for the freeway-related chapters

The HCM service measure concept is intended to be user-oriented, rather than system-oriented. That is, measures that the user may readily perceive, such as speed and travel time, delay, and density, serve as the parameters for level of service determination. System-oriented measures, such as volume to capacity ratio and vehicle-miles of travel (VMT), are not experienced by the typical user, and therefore do not meet the principal service measure criterion. Included in the Draft HCM 2000 are methodologies for determining the system performance of multiple facilities, corridors, and an area or region (1998b). For example, the draft Chapter on "Assessment of Multiple Facilities" of the HCM 2000 presents the analytical framework for determining the performance of area wide and corridor analyses for transportation systems containing multiple facilities and modes. Interestingly, the document does not specify any facility-wide service measures. Rather, it states that such letter-grade classification should be left to the local agencies, since traveler expectation varies by size of the area and geographical location. On the other hand, the document states that "system performance must be measured in <u>more than one dimension.</u>" Further, it goes on to describe that

> the degree to which travelers are satisfied with a particular travel experience is dependent upon the options that they think are available to them and their perception of historical experience (HCM, 1998b).

The draft "Corridor Analysis" and "Areawide Analysis" chapters (HCM, 1998c; HCM, 1998d) also provides detailed procedures regarding the analysis of large study areas but at a much coarser level. Much of the MOE selection methods that appear in the HCM2000 draft were originally proposed by May (1996) as part of NCHRP 3-55(4).

Baumgeartner (1996) investigated alternative methods of reporting degrees of failure of a facility (or LOS F). Noting that traffic congestion in the 1990s has increased dramatically since the 1960s, research related to reporting degrees of success (LOS A through D, and sometimes E) has greatly outpaced that devoted towards reporting degrees of failure (LOS F). He proposes three possible options to describe facility performance even under congested conditions. The first would expand the traditional range beyond LOS A through F to include G, H, I as additional thresholds. The second would report the performance beyond the traditional peak period, using a multiple-hour base to report conditions at or worse than LOS D. The third option assigns a numerical grade to the level of service for a facility or intersection (using an expanded LOS range) multiplied by the amount of hours at the specified level of service. This would result in a numerical grade or "Congestion Index" on which to base the degree of congestion. Lastly, the document presents proposed modifications of existing LOS for intersections and arterials, with reference to research conducted by Cameron (1996).

In an unpublished paper, Ostrum (1998) explores the development of a system level of service. The author uses system density as the service measure, consistent with HCM techniques for uninterrupted facilities. To account for spatial and temporal changes in density, the author proposes the use of percentage of total lane kilometers ($p_{ln\text{-}km}$) and percentage of travel time (p_{tt}) along a facility or corridor. These variables are then multiplied to yield a cumulative density for the specified area. Upon developing a density cumulative distribution function, she proposes thresholds for system levels of service A through F. While the author has proposed a creative approach in determining a system level of service (which has spurred us to test these concepts with real-word data), she does not explore the possibility of using speed or density cumulative distribution functions based on how frequently a driver perceive such conditions. This implies that speed (or density) should be weighed by the proportion of the facility travel time over which the indicated speed (or density) is encountered.

3. DESCRIPTION OF FIELD DATA SETS

The field data for this work consists of seven congested directional freeway facilities in North America having varying numbers of segments and time intervals, and one additional site in Europe. Collected by various cooperating agencies for use by the research team that has developed the freeway facility chapter in the HCM2000, these congested sites include under-saturated and over-saturated segments and a range of free flow speeds (FFS). Sites are widely dispersed in New York (NY), Ontario (CA and ONT), Missouri (MO), Washington (WA), Wisconsin (WI), and Denmark (DK). Each of the seven freeway data sets vary by such characteristics as number of total segments, off-ramps, on-ramps, weaving sections, time periods, free flow speeds, and length. The general characteristics for each site are shown in Table 1 below. Listed are the facility free flow speed (FFS), number of sections (between ramps), and segments (basic, ramp or weaving segment), the length of the directional facility (mi), the total number of 15-minute time intervals, and the number of congested time intervals. Additional details on those sites can be found elsewhere (May 1999).

TABLE 1 Summary of Site Characteristics

Site	FFS (mph)	# of sections	# of segments	Length (mi)	# time intervals	Congested sections*	Congested intervals**
CA	65	5	7	2.8	12	4	11
DK	65	16	23	8.5	10	12	8
MO	65	20	28	8.7	9	11	9
NY	65	6	11	3.9	5	3	2
ON	55	6	6	2.5	12	4	9
WA	65	6	10	4.7	12	4	8
WI	65	17	25	6.7	12	14	8

*****sections with average speed below 50 mph in any time interval.
******time intervals in which the average speed on *any* section drops below 50 mph.

At all sites, the average speed on each section was reported in each 15-minute interval. These speeds were obtained using either a floating car, or a surveillance system that can measure speed directly (using dual-loop detection), or estimate it from flow and occupancy (single-loop detection). Field-measured density was not available at most sites, and therefore is not included in this analysis. An example of the speed observations at two sites (WA and MO) is depicted in Figure 1. The light shaded cells represent speeds under 50 mph, while the dark-shaded cells represent speeds under 30 mph. The WA site appears to be uncongested during the first three time intervals, while the congestion at the MO site is confined to sections 7 through 17. These are good examples that can illustrate the consequences of how the facility is defined in the time-space domain and their eventual impact on the reported quality of service.

4. FIELD DATA ANALYSIS

The analysis is presented in two parts. The first deals with aggregate measures of performance, in particular the mean and median facility speeds. The intent of this part is to understand the impact of defining the facility boundaries (in time and space) on its ultimate service measure. This may help future analysts to better define such boundaries. The second approach is more microscopic and deals with the segregation of service measure data in time and space. This leads to the concept of cumulative distribution curves and their use for defining LOS, as proposed by Ostrom (1998).

4.1 Aggregate Service Measures

4.1.1 Entire time space domain

Based on the speed data illustrated in Figure 1, an aggregate service measure can be derived over the entire time space domain, that is, over all sections and all time intervals. The authors call this measure the facility mean speed. Table 2 below shows the facility mean speed at each site, and the corresponding LOS. The designation of LOS is based on the 1997 HCM basic freeway section procedure, which uses the facility FFS to determine the minimum speed required to meet the LOS. It is evident from Table 2 that all seven facilities operate at a very poor LOS (E or F), although the facility mean speed varies widely from a low of 44.3 mph to 56.5 mph. For comparison purposes, the median speed at each site is also shown in parentheses.

TABLE 2 Facility-Mean (Median) Speed Aggregated over All Speed Cells

Site	# of speed cells	Facility FFS	Facility-mean (median) speed	LOS
CA	60	65	44.3 (42.6)	F
DK	160	65	44.5 (40.6)	F
MO	180	65	50.6 (49.5)	F
NY	30	65	56.5 (55.5)	E
ON	72	55	50.0 (49.8)	E
WA	72	65	48.8 (53.1)	F
WI	204	65	51.5 (51.5)	F

4.1.2 Excluding undersaturated time intervals

An examination of Table 1 and Figure 1 indicates the presence of several time intervals in which traffic was flowing close to free flow conditions. By redefining the facility time-space domain to include only those intervals where congestion occurs, another set of facility-mean (median) speeds and LOS are estimated. These results are depicted in Table 3 below. While the difference in LOS are not significant (all sites are at LOS F), the magnitude of the change in facility mean speed is quite significant, exceeding 4 mph in four of the seven sites. Thus, the manipulation of which time intervals to include or exclude from the analysis can have a substantial impact on the resulting performance. Table 3 also shows that the median speed is consistently lower than the mean speed when the under-saturated intervals are excluded.

4.1.3 Excluding undersaturated sections

An examination of Table 1 and Figure 1 indicates the presence of several sections in which traffic was flowing close to free flow conditions. By redefining the facility time-space domain to include only those sections where congestion occurs (but over all time intervals), a third set of facility-mean (median) speeds and LOS can be estimated. These results are depicted in Table 4 below. While the difference in LOS are again not significant (all facilities are at LOS F), the magnitude of the change in facility mean speed in quite significant, close to 4–5 mph on average. Thus, the manipulation of which sections to include or exclude from the analysis can also have a substantial impact on the resulting facility performance.

TABLE 3 Facility-Mean (Median) Speed Aggregated over Congested Intervals Only

Site	# of speed cells	Facility FFS	Facility-mean (median) speed	Reduction from Table 2	LOS
CA	55	65	42.9 (42.0)	-1.4 (-0.6)	F
DK	128	65	40.2 (37.4)	-4.3 (-3.2)	F
MO	180	65	50.6 (49.5)	0.0 (0.0)	F
NY	12	65	51.7 (49.8)	-4.8 (-5.7)	F
ON	54	55	47.3 (46.4)	-2.7 (-3.4)	F
WA	48	65	42.0 (38.8)	-6.8 (-14.3)	F
WI	136	65	46.7 (47.4)	-4.8 (-4.1)	F

TABLE 4 Facility-Mean Speed Aggregated over Congested Sections Only

Site	# of speed cells	Facility FFS	Facility-mean (median) speed	Reduction from Table 2	LOS
CA	48	65	41.4 (39.4)	-2.9 (-2.8)	F
DK	120	65	40.1 (35.1)	-4.4 (-5.5)	F
MO	90	65	41.4 (39.2)	-9.2 (-10.3)	F
NY	15	65	52.7 (48.3)	-3.8 (-7.2)	F
ON	48	55	47.9 (47.6)	-2.1 (-2.2)	F
WA	48	65	45.5 (51.9)	-3.3 (-1.2)	F
WI	156	65	48.8 (48.7	-2.7 (-2.8)	F

	Section #					
Time Interv.	**1**	**2**	**3**	**4**	**5**	**6**
1	62.0	60.0	59.0	60.0	55.0	61.0
2	58.0	56.0	58.0	60.0	52.0	52.0
3	60.0	59.0	59.0	61.0	53.0	50.0
4	55.0	60.0	61.0	58.0	55.0	60.0
5	50.0	61.0	60.0	35.0	54.0	54.0
6	44.0	48.0	***21.0***	***18.0***	51.0	51.0
7	***23.0***	36.0	***17.0***	***19.0***	52.0	59.0
8	***24.0***	38.0	***14.0***	***21.0***	58.0	50.0
9	59.0	***21.0***	***15.0***	***20.0***	56.0	59.0
10	60.0	37.0	***19.0***	***23.0***	54.0	60.0
11	61.0	59.0	51.0	38.0	54.0	60.0
12	63.0	60.0	62.0	61.0	55.0	62.0

FIGURE 1(a) Mean speed by section and time interval—Washington.

Time Interv.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	63.6	62.4	62.3	63.7	62.8	62.7	62.5	59.7	61.0	59.3	46.6	49.3	55.0	53.0	54.5	57.9	55.9	55.2	55.0	56.2
2	62.6	63.0	62.2	62.8	59.8	59.7	60.5	53.6	44.2	35.3	***19.2***	***21.4***	35.5	40.6	42.8	51.4	48.3	52.4	52.1	53.2
3	58.5	59.2	59.6	59.9	59.1	62.3	62.9	62.6	57.1	46.7	43.0	49.6	49.2	48.2	49.1	56.7	57.0	57.6	58.4	53.0
4	60.6	55.2	53.5	55.7	55.9	50.2	51.9	***16.7***	***9.5***	***10.2***	***14.3***	***18.9***	***18.9***	***25.0***	33.3	36.8	46.8	53.3	51.8	55.6
5	63.6	62.8	62.9	63.0	62.9	64.3	63.4	58.1	46.4	***29.1***	***14.7***	***20.1***	30.8	34.7	38.9	51.0	53.8	55.6	57.1	56.5
6	60.5	60.6	61.3	61.2	60.1	59.8	59.5	47.5	43.0	33.1	***18.7***	***25.6***	32.6	33.9	35.8	48.6	54.4	57.7	56.6	55.7
7	64.4	64.3	64.0	64.3	64.3	64.0	64.2	56.7	***25.4***	***10.7***	***17.5***	***21.5***	***21.0***	***24.8***	36.8	49.0	53.0	54.5	56.2	56.3
8	63.3	64.1	63.9	64.0	63.0	63.5	62.7	61.7	55.0	34.9	33.1	38.1	***25.0***	***23.1***	32.8	44.2	56.5	58.9	57.5	55.2
9	64.0	62.7	63.0	63.8	63.6	63.3	62.9	63.4	63.1	61.6	54.7	57.4	58.1	47.3	45.2	54.8	58.2	58.1	54.0	55.1

FIGURE 1(b) Mean speed by section and time interval—Missouri.

4.1.4 Excluding undersaturated sections and time intervals

Table 5 shows the combined impact of including only those intervals that exhibit congestion, and only for those sections that experience that congestion. In Figure 1, that means excluding any rows and columns that have no shaded cells. Obviously, this process yields (a) a much smaller sample size of cells, and (b) much more congested operations and therefore larger differences in speeds from those measured across the entire time space domain in Table 2. These differences average slightly above 10 mph, and vary across sites depending on the prevailing congestion level at each site.

In summary, the aggregate analysis has demonstrated the significant effect of section and interval selection in estimating the facility service measure. The seven data sets spanned a wide range of congestion levels. The percent of total cells "in congestion" ranged from 13% at the NY site, to close to 70% at the CA site. Under these conditions, the expectation is that removing the undersaturated time intervals will cause a mean facility speed reduction of 4 mph. Similarly, removing all uncongested sections from the analysis causes a similar speed reduction. Removing both causes a large average speed reduction of close to 10 mph. Larger differences can be expected if the fraction of uncongested cells is high (e.g., WA and NY sites) and vice versa (e.g., CA and ON sites).

4.2 Disaggregate Service Measures

Data were first disaggregated in time and space before generating the required service measure. Thus, each time interval is considered as a separate entity. Spatial disaggregation within an interval is accomplished using the following process:

1. calculate average travel time per vehicle on each section and for the entire facility
2. calculate the proportion of facility travel time expended within each section
3. develop a cumulative speed distribution using the section travel time proportions as the weighting frequency measure.

To determine the speed value upon which to base the facility LOS requires that:

(a) one specific time interval be selected (could be the most congested one or any designated lower percentile—i.e., highly congested interval) and

(b) a designated percentile speed in the selected interval be chosen to represent the service measure (could be 50 or 85^{th} percentile speed).

TABLE 5 Facility-Mean (Median) Speeds for Congested Sections and Intervals Only

Site	# of speed cells	Facility FFS	Facility-mean (median) speed	Reduction from Table 2	LOS
CA	44	65	39.8 (38.8)	4.5 (3.8)	F
DK	96	65	34.8 (31.5)	9.7 (9.1)	F
MO	90	65	41.4 (39.2)	9.2 (10.3)	F
NY	6	65	41.0 (41.0)	15.5 (14.5)	F
ON	45	55	42.3 (43.5)	7.7 (6.3)	F
WA	28	65	35.4 (32.8)	13.4 (20.3)	F
WI	104	65	42.6 (43.4)	8.9 (8.1)	F

For example, the analyst could define a single facility LOS on the basis of the observed 85th percentile speed (or density) which occurs in the top 15th percentile congested time interval. Therefore, if 20 time intervals were ranked based on mean speed, from most congested (Rank 1) to least congested (Rank 20), then speeds in the time interval with Rank 3 are used to designate the LOS. Alternatively, a service measure can be computed for each time interval separately. Both these concepts are illustrated in Figure 2. Depending on the interval selected, the range of the service measure can vary by up to 10 mph.

Speed distributions were developed for the seven field sites using the two data disaggregation scheme described above. For each site, service measures were first computed for each time interval separately, and then a single representative speed at the 15th percentile time interval was extracted. LOS thresholds are adjusted from the current HCM means speed thresholds to 85th percentile speed equivalents. This was done assuming a normal distribution of speeds within a time interval, and a standard deviation equivalent to 10% of the mean speed. For example, at FFS = 55 mph, the basic section LOS D threshold for mean speed is 54.5. The equivalent threshold for the 85th percentile speed can be shown to be 1.1035 $\times$ mean speed = 60.14 mph. The speed and LOS results for the seven sites are summarized in Table 6 and discussed next.

It appears that the elaborate time and space disaggregation still cannot eliminate the bias in LOS caused by artificially extending the time-space domain to include undersaturated time intervals and segments. Even when only the worst time interval at each site is used to determine LOS, the resulting speeds are still quite high (see for example MO, NY and WI). This problem is likely to occur whether speed, density or any other MOE is used. These observations clearly indicate that by only removing all sections that are fully undersaturated

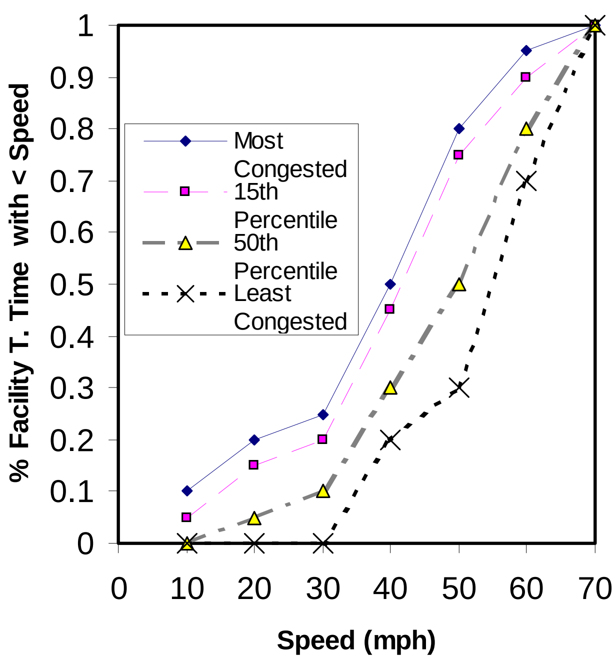

FIGURE 2 Illustration of speed distributions by time interval.

across the entire analysis period, as well all time intervals that contain any oversaturated sections can a true measure of facility congestion be ascertained. In Figure 1a, this process would eliminate sections 5 and 6 and time intervals 1-4, 11-12 from consideration. The remaining cells will basically cover the bottleneck(s) section and all upstream segments that are effected by it (them). Obviously, if no cell in the time space domain is oversaturated, then simple aggregation of the service measure across all cells may be sufficient.

5. CONCLUSIONS

This paper summarizes an effort to overcome the problem of aggregating service measures for freeway facilities for the purpose of designating a facility LOS. Using real-world speed data at seven sites in North America and Europe, various aggregation and disaggregation schemes were tested. It was found that by excluding oversaturated sections, or oversaturated intervals, the mean facility speed drops by about 5 mph for the range of data explored. The combined effect was additive yielding speed differences near 10 mph. A cumulative distribution approach discussed in the literature was tested in this study but again could not overcome the spatial aggregation problem. While it is critical that the time-space domain contain undersaturated segments and time intervals for the purpose of ensuring that the congestion is fully contained within the domain, the designation of LOS should not include the entire time space domain. In conclusion, we propose the following process for facility LOS determination:

1. Select the time-space domain to ensure that all congested sections and time intervals are contained within it.
2. Estimate for each cell in the domain the average speed or density, and define over-capacity speed or density thresholds (typically 50 mph and 45 pc/mi/lane, respectively).
3. Identify all sections that are below the congestion thresholds in all time intervals. Eliminate them from further consideration (e.g., sections 5 and 6 in Figure 1a).
4. Identify all time intervals that are below the congestion thresholds across all sections. Eliminate them from consideration (e.g., intervals 1-4, 11-12 in Figure 1a).
5. Calculate the space mean speed or density for the remaining cells. Use appropriate thresholds to estimate the facility LOS.

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TABLE 6 Speed and LOS Results from the Disaggregate Analysis Approach

Site	85TH Percentile Speed and LOS in Indicated 15-Min Time Intervals											85TH Percentile Speeds in the 15TH Percentile Interval
	T=1	2	3	4	5	6	7	8	9	10	11	12	
CA	58.88 E	55.75 F	49.67 F	48.55 F	46.45 F	45.55 F	47.45 F	**42.86** **F***	46.45 F	45.45 F	45.62 F	46.58 F	45.51 (F)
DK	63.82 E	60.40 E	38.87 F	**37.30** **F**	37.30 F	44.25 F	53.00 F	58.00 E	60.92 E	63.58 E	-------	-------	37.85 (F)
MO	62.80 E	62.17 E	62.21 E	**53.60** **F**	62.89 E	60.57 E	64.17 E	63.25 E	63.50 E	------	-------	-------	61.68 (E)
NY	64.42 E	59.06 E	**55.00** **F**	59.00 E	66.44 E	-----	-----	-----	-----	-----	-----	------	57.40 (E)
ON	60.63 C	60.63 C	59.63 E	57.42 E	**55.35** **E**	56.29 E	53.29 E	56.32 E	57.35 E	58.42 E	59.44 E	56.61 E	55.96 (E)
WA	61.64 E	57.87 E	59.85 E	59.61 E	59.60 E	50.25 F	**35.83** **F**	37.83 F	58.53 E	59.59 E	60.62 E	62.69 E	45.90 (F)
WI	61.91 E	61.88 E	60.30 E	59.38 E	59.29 E	58.17 E	**48.63** **F**	56.25 F	59.25 E	62.12 E	62.83 E	63.00 E	57.50 (E)

***Most congested time interval at each site shown in bold.

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